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# DEPARTMENT OF THE NAVY
## U. S. NAVAL AIR DEVELOPMENT CENTER
JOHNSVILLE
WARMINSTER, PA. 18974

Aero-Electronic Technology Department

REPORT NO. NADC-AE-6731 13 September 1967

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**WATER DRAG EFFECTS OF FLOW INDUCED CABLE VIBRATIONS**

**PHASE REPORT**
**AIRTASK NO. A37533000/2021/F101-13-07**
**Work Unit No. 170**

A study was performed on smooth, circular, flexible cables to determine the water drag characteristics that are dependent upon the cable strumming phenomenon. The test cable diameters ranged from 0.057 to 0.140 in. and the Reynolds numbers were within 300 to 1300. The study was a prerequisite to developing cables with low drag and low strumming characteristics.

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Sonar Sensors Division

J. M. McCandless

Approved by: H. Suter, Superintendent
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# SUMMARY


## INTRODUCTION

Single-element or multiple-element hydrophones used with moored or drifting sonar systems are suspended by complex arrangements of long or short cables of circular cross section. These cables are usually exposed to relative water flows in the 1/4- to 3-kn range, caused by in situ currents or induced by the capricious effects of wind and waves.

The water flowing past the cable induces periodic, transverse vibrations, commonly called "cable strumming." This strumming is initially excited by localized low-pressure zones along the side of the cable. The zones alternate periodically from side to side, thereby producing alternating side thrusts. The zones are related to the flow separation and vortex formations near the base of the cable (cylinder). Vortices are shed into the flow wake and form on alternate sides of the flow centerline (von Karman vortex wake). The strumming of the cable interferes with sonar functions by causing pseudoacoustic signals[1] from the hydrophones and adverse cable drag[2].

## RESULTS

Flexible cable drag coefficients can be determined to within 10 percent by measuring the cable drag angle of a towed streaming cable with a terminal weight standard.

A tractable analytical drag model was formulated to express the normal strumming drag coefficient $C_{Ds}$ in terms of the normal drag coefficient $C_D$, cable diameter $d$, and mass per unit length $m_c$ of the cable. The model represents the strumming cable as a circular cable with a larger diameter, termed the virtual diameter. The expression for the strumming drag coefficient has the form,

$$C_{Ds} = C_D \left[1 + a\left(\frac{d^2}{m_c}\right)^{1 + \alpha}\right],$$

Verification of this concept is shown for cables with different diameters and different values of mass. The best-fit values for the constants are $a = 10$ and $\alpha = 1$. With a nominal value of 0.195 $ft^4/lb\text{-}sec^2$ for $d^2/m_c$ an approximate criteria for the strumming normal drag coefficient is 38 percent higher than that of a circular cylinder.


1. *Dale, J. R. and Menzel, H. R., Dec 1965; Flow Induced Oscillations of Hydrophone Cables; NAVAIRDEVCEN; 23rd Naval Underwater Sound Symposium Proceedings; ONR Rpt ACR-115 Paper 3A6 Pg 411.*
2. *Dale, J. R., Dec 1966; Hydrodynamic Analysis of the AN/SSQ-41 Sonobuoy Hydrophone Suspension System; NAVAIRDEVCEN Report No. NADC-AE-6636.*

## CONCLUSIONS

Transitional nominal variations in the drag coefficient of 30 percent are shown to correspond to tone effects, characteristic of a strumming cable in a varying flow. These transitions occur at discrete water velocities for a given cable length and can be defined by the classical string equation and Strouhal number.

Envelope values for the strumming normal drag coefficient of a smooth circular flexible cable can be predicted by:

$$C_{Ds} = C_D \left[1 + 10\left(\frac{d^2}{m_c}\right)^2\right].$$

where d is the cable diameter and $m_c$ is the virtual mass of the cable per unit length. This equation has been verified for cables from 0.057 to 0.140 in. in diameter and for a mass range of $1.16 \times 10^{-4}$ to $9.30 \times 10^{-4}$ slug, within the Reynolds number range 300 to 1300.

# TABLE OF CONTENTS

## LIST OF FIGURES

# LIST OF SYMBOLS

| | |
|---|---|
| $a$, $a'$, $a''$ | = Experimental constants |
| $C/C_c$ | = Damping ratio for the vibrating cable |
| $C_D$ | = Dimensionless normal cable drag coefficient based on d for normal flow past a smooth circular cylinder |
| $C_{Ds}$ | = Dimensionless normal cable drag coefficient based on d for normal flow past a strumming cable |
| $C_L$ | = Cable lift coefficient |
| $d$ | = Cable diameter |
| $d_p$ | = Equivalent diameter of the cable projected on a transverse plane |
| $d_v$ | = Virtual cable diameter (defined in appendix A) |
| $f$ | = Frequency of the transverse cable vibrations |
| $f_c$ | = Normal drag force per unit length of the cable |
| $F$ | = Alternating periodic strumming force which accelerates the fixed end mass |
| $g$ | = Gravitational constant |
| $K_x$ | = Spring constant of cable in transverse direction |
| $L$ | = Cable length |
| $\ell$ | = Distance between nodes for any specified wave segment |
| $m_c$ | = Virtual cable mass per unit length (physical mass plus mass of an equivalent volume of water) |
| $n$ | = Number of vibrating cable segments in the cable length L, $n = L/\ell$ |
| $N_{Re}$ | = Dimensionless Reynolds number = $du_n/\nu$ |
| $r$ | = Amplitude of transverse cable vibrations |
| $S_t$ | = Dimensionless Strouhal number = $fd/u_n$ |
| $T$ | = Tension in the cable |
| $u_o$ | = Free stream water velocity |
| $u_n$ | = Component of water velocity normal to the cable |
| $u_t$ | = Harmonic velocity of the vibrating cable = $2\pi fr$ |
| $\alpha$ | = Experimental constant |
| $\Delta$ | = Increment of the parameter |
| $\rho$ | = Density of water |

LIST OF SYMBOLS (continued)

$\nu$ = Kinematic viscosity of water

$\sigma$ = Factor expressing effectiveness of flow blockage, defined in appendix A

$\omega$ = Angular forcing frequency

$\omega_n$ = Angular natural frequency of any standing wave segment

# D I S C U S S I O N

## BACKGROUND

The dependence of normal cable drag on cable strumming was observed on free streaming cables with terminal weights[1]. Small variations in cable angle were observed simultaneously with changes in vibration amplitude. The dependence of drag on rigid cylinder oscillations was shown by Bishop and Hassan[3]. When their rigid cylinder was forced to oscillate at a frequency in counterpoint with the natural wake frequency, an increase in drag was observed. Also, this dependence has been inferred by high amplitude transverse, resonant vibrations. Windhorst[4] reports such a condition for a spring mounted rigid cylinder when the natural vortex shedding frequency coincided with the spring-mass natural frequency.

The authors[5] have reported on similar resonant amplitudes as well as cable tone effects on flexible cables. Transverse standing wave vibrations were forced by the interaction of the water flow with the cable. When the flow velocity was gradually varied, transitions in amplitude and frequency were reported at discrete velocities each time the number of standing waves changed by one. The frequency interval between successive transitions and a specific standing wavelength characterized a numbered partial vibration mode. (The term partial is used instead of harmonic because the frequencies are not even multiples of the fundamental.) Correlation was obtained with the string equation,

$$L = \frac{n}{2f} \sqrt{\frac{T}{m_c}} \qquad (1)$$

where the forcing frequency was approximately defined by the Strouhal number,

$$S_t = \frac{fd}{u_0} \qquad (2)$$

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1. *See pg iii.*
3. *Bishop, E. D. and Hassan, A. Y., May 1963; The Lift and Drag Forces on a Circular Cylinder Oscillating in a Flowing Fluid; University College, London, Dept of ME.*
4. *Meier-Windhorst; Aug 1939; Flow Induced Vibrations of Cylinders in Uniform Flow; Munich Technische Hochschule, Hydraulische Inst. Mitt, Heft 9.*
5. *Dale, J. R., et al, Sep 1966; Dynamic Characteristics of Underwater Cables - Flow Induced Transverse Vibrations; NAVAIRDEVCEN Report No. NADC-AE-6620.*

The amplitude of each standing wave vibration is a minimum for the velocity just prior to each transition - frequently zero. Within each partial mode, a maximum amplitude is reached when the forced vibration frequency equals the natural cable frequency of the vibrating segments. The normal drag coefficient was expected to be directly dependent on these amplitude variations.

DRAG AND STRUMMING MEASUREMENTS

Because of the dependence of cable drag upon cable strumming, diagnostic instrumentation was developed to measure both effects simultaneously.

## Cable Drag Coefficient

An experimental technique was developed to determine $C_{DS}$ for normal flow by towing a test cable through water. (The symbol $C_{DS}$ is used to designate the normal drag coefficient for a strumming cable, while $C_D$ is used for a nonstrumming cylinder.) The lower free end of the cable was attached to a smooth surfaced, 2-in. diameter, 0.504-lb sphere, used as a standard of known weight and known velocity dependent drag force. The cable drag angle at the tow point was measured photoelectrically using a rotating vane, and correction was made for the bow in the streaming cable. The normal water force per unit cable length was determined by summing the force moments about the tow point. The normal $C_{DS}$ was computed by using this force and the actual cable diameter.

The accuracy of the $C_{DS}$ determination was enhanced by a prudent selection of cable length and drag to weight ratio of the sphere standard. Cable lengths from 3 to 4 ft were used because longer cables generally are excited with multiple frequency beating effects which obscure the classical signature of the strumming signal. The $C_{DS}$ determination was estimated to be valid within 10 percent when the angle and velocity were measured to 2 and 3 significant figures, respectively.

## Strumming Force

The periodic strumming forces, representing cable tension oscillations, were determined by measuring the accelerations of a spring mounted mass. The mass and spring supported the cable at the tow point (fixed end). The spring constant and mass were selected such that the spring restoring force was small compared to the force to accelerate the mass. Accordingly, the force determination was essentially the product of mass times acceleration.

The instrumentation, is shown in figure 1. The test cable was towed by a rotating arm with a 7-ft radius. During each test the angular velocity of the arm was varied such that the free stream tow velocity gradually decreased from 1.2 to 0 kn in approximately 2 min. This provided data over the Reynolds number range of interest, and spanned several partial vibration modes.

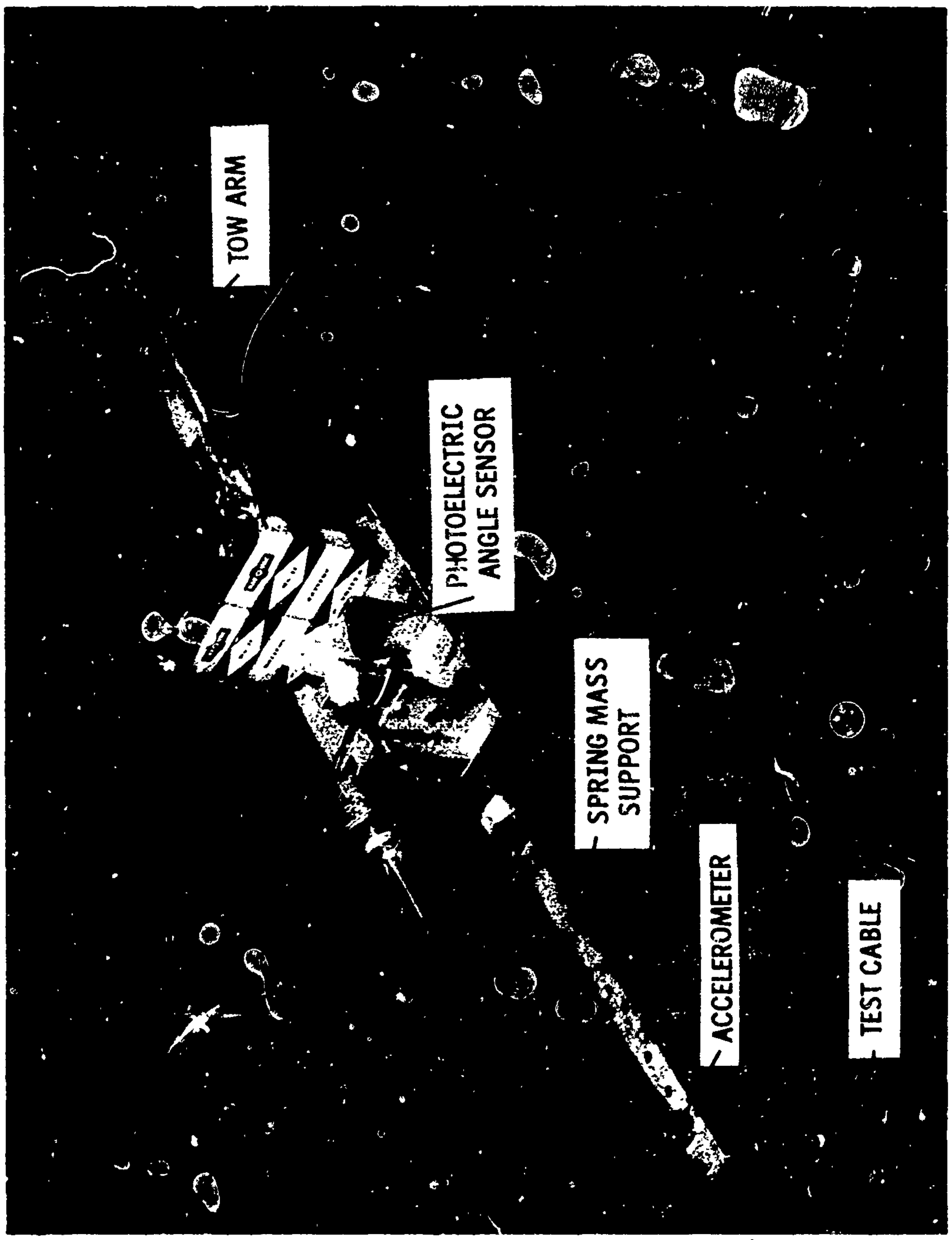


FIGURE 1 - Instrumentation for Measurement of Cable Drag Angle and Strumming Accelerations

A segment of the raw data recording for a 0.107-in. diameter, 36-in. long cable is illustrated on figure 2. Three partial vibration modes are indicated by the three triangular forms of the acceleration signal. Starting from the high velocity end these modes correspond to the fourth, third, and second partials with half wavelengths of 9, 12, and 18 in. respectively. The trace of the cable drag angle humps during these partial vibrations, indicative of an increase in cable drag. The cable drag angle is responsive to the unstable bursts preceding the amplitude transitions of the acceleration trace.

The normal drag coefficient, $C_{D_S}$, for the strumming cable, and the periodic strumming force are plotted against Reynolds number in figure 3. The normal drag coefficient, $C_D$, for a nonstrumming circular cylinder is also plotted as a reference. Each sawtooth form represents a discrete partial vibration. The minimum points were between the partials or near the transitions where the cable vibrations decayed to a low level. As indicated, the minimum points approached the nonvibrating $C_D$ reference plot, which was expected for the low level vibrations. Both $C_{D_S}$ and F show the same phase relationship. This implies that the drag is related to the amplitude of vibration, because the cable tension variation F is in phase with the elongation of the cable or transverse amplitude. The peak values must represent the true partial vibration, where the natural frequency for that particular standing wave is in counterpoint with the frequency of the water exciting function. This resonance effect is presented in more detail by Windhorst[4] and the authors[5].

The maximum and minimum points of these sawtooth characteristics occur at different $N_{Re}$ when the cable length is changed. This can be seen from the string equation (1), where a change in L will result in a different f for the same numbered partial n. The water forces excite the cable at this new f at a different velocity or $N_{Re}$. The peak values of the parameters, therefore, describe an envelope which is independent of cable length. (Envelope values will be inferred with reference to $C_{D_S}$ and F for the balance of this work.)

## ANALYTICAL MODEL

Present scaling laws[6], describing the drag of bluff bodies, relate the drag to appropriate parameters of the near wake. These parameters are associated with the well known alternately shedding vortices (Karman wake). The near wake characteristics of a strumming flexible cable are

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4. *See pg 1.*
5. *See pg 1.*
6. *Roshko, A., Feb 1955; On the Wake and Drag of Bluff Bodies; J of Aero Sciences; Pg 124.*

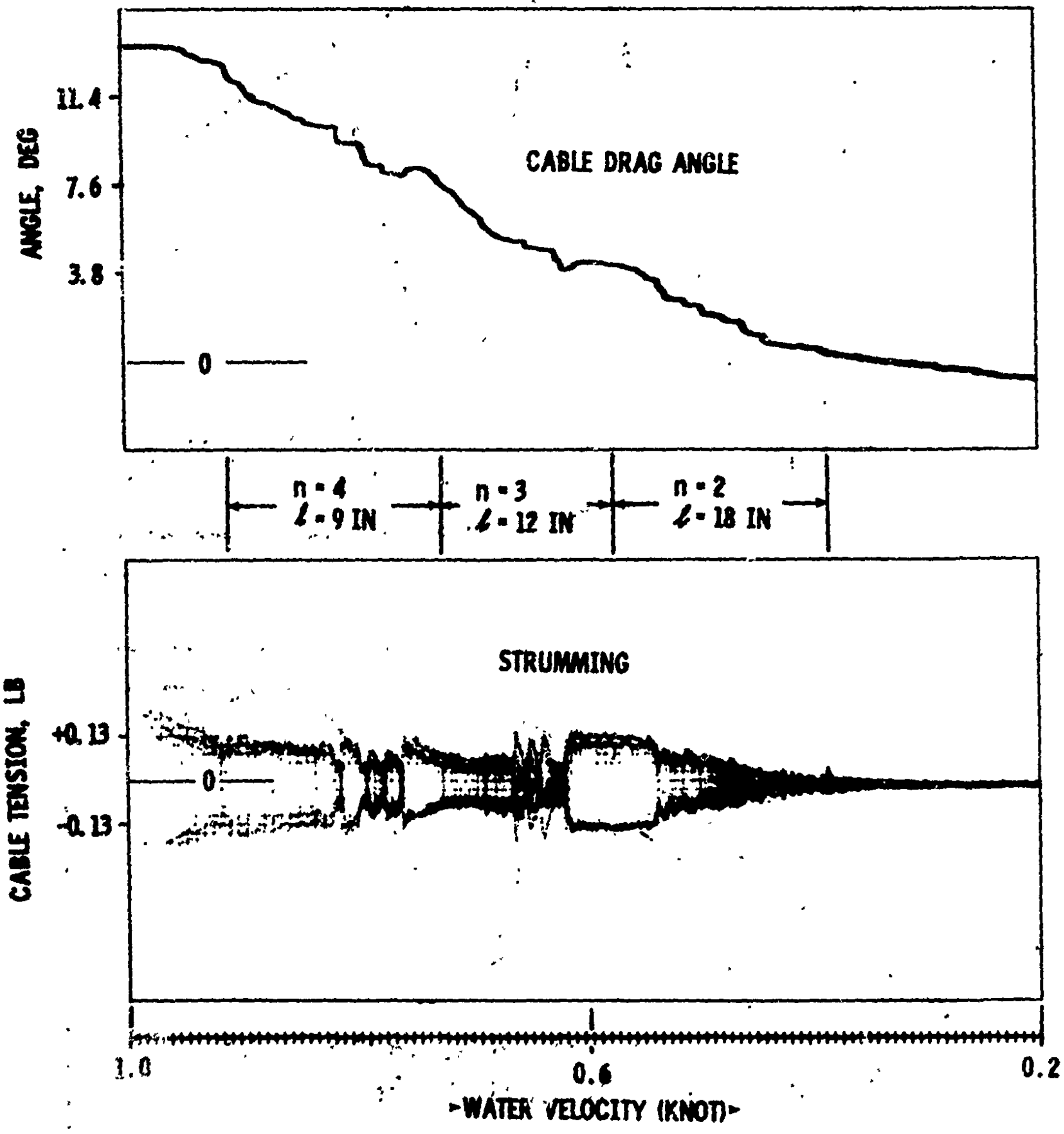


FIGURE 2 - Acceleration (Strumming) and the Cable Drag Angle Signatures for a 0.107 In. Diameter Cable in a Gradually Decaying Flow. One Second Time Pulses Indicated.

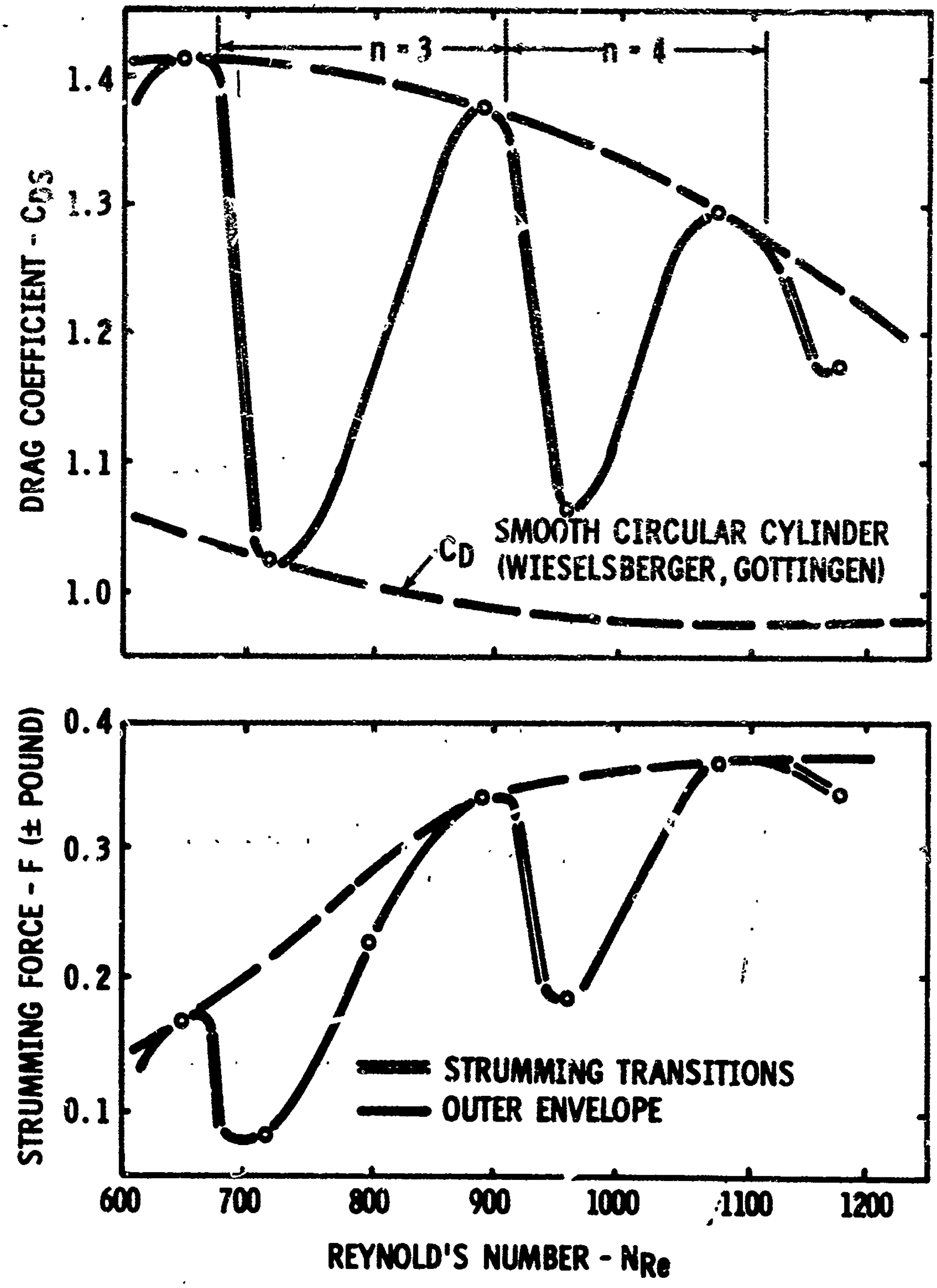


FIGURE 3 - Strumming Drag Coefficient and Strumming Force for a Smooth Cylindrical Cable 0.107-In. Diameter, 3 Ft Long

known to deviate from the classical Karman wake concept[4, 7]. Because of the lack of guidelines to formulate a tractable drag equation for the strumming cable, a drag model with a virtual diameter was postulated.

The transverse vibrations of a smooth circular strumming cable are assumed to appear to the flow as a larger diameter (virtual diameter, $d_V$), smooth, circular, nonstrumming cable. The virtual diameter is then related to the equivalent projected diameter times a factor which expresses the effectiveness of this projected diameter in blocking the flow. This effectiveness factor is the ratio of the assumed harmonic transverse cable velocity to the free stream velocity.

The strumming cable drag coefficient for normal flow has the form:

$$C_{Ds} = C_D \frac{d_V}{d} = C_D \left(1 + \frac{\Delta d_p}{d} \sigma\right). \qquad (3)$$

In terms of cable parameters the equation reduces to:

$$C_{Ds} = C_D \left[1 + a \left(\frac{d^2}{m_c}\right)^{1 + \alpha}\right], \qquad (4)$$

where $a$ and $\alpha$ are constants to be determined from experimentation. $C_{Ds}$ is seen to be dependent only on the drag coefficient $C_D$ for a circular nonstrumming cable of diameter d, the cable diameter d, and the cable virtual mass per unit length $m_c$. Details of this derivation are presented in appendix A.

## EXPERIMENTAL STUDY

Equation (4) was verified by experimental determination of $C_{Ds}$ over a diameter range from 0.037 to 0.140 in. and a $d^2/m_c$ range from 0.123 to 0.315 ft$^4$/lb sec$^2$. All cables were smooth and flexible with circular sections. (A cable is considered flexible when the internal reacting bending moments are small relative to the external bending moments.)

Corresponding cable parameters are listed in table I. Each test cable was towed through a gradually decreasing velocity range from about 1.2 to 0 kn. The drag angle and the periodic accelerations of the fixed end mass were measured simultaneously.

4. *See pg 1.*
7. *Schindel, L. H., et al, Oct 1936; An Investigation of Forces on an Oscillating Cylinder for Application to Ground Wind Loads on Launch Vehicles; MIT Aerophysics Lab TR 130.*

## TABLE I

### CABLE PARAMETERS

| d (in.) | $m_c$ (lb $sec^2$ $ft^2$) | $d^2/m_c$ ($ft^4$/lb $sec^2$) | Measured $C_{Ds}/C_D$ | *Equation (2) $C_{Ds}/C_D$ |
|---|---|---|---|---|
| 0.057 | $1.16 \times 10^{-4}$ | 0.195 | 1.25 | 1.38 |
| 0.107 | $4.[illegible]5 \times 10^{-4}$ | 0.195 | 1.36 | 1.38 |
| 0.128 | $3.[illegible]0 \times 10^{-4}$ | 0.315 | 2.00 | 1.99 |
| 0.128 | $9.30 \times 10^{-4}$ | 0.123 | 1.04 | 1.15 |
| 0.140 | $6.84 \times 10^{-4}$ | 0.199 | 1.52 | 1.40 |

* For experimental scaling constants a = 10, and $\alpha$ = 1.

By interpreting the numbered partial vibration modes from the acceleration signature, the highest $C_{Ds}$ value for each specific partial was determined. The highest $C_{Ds}$ value was generally found where the acceleration amplitude was the highest. This generally coincided with the hump in the drag angle trace. In this way the envelope of the $C_{Ds}$ values was defined for each cable. Three cables were selected with approximately the same $d^2/m_c$ ratio of 0.195 $ft^4$/lb $sec^2$ but with diameters of 0.057, 0.107, and 0.140 in. (Insulated electrical cables over a wide range of diameters will generally have ratios around this value since $m_c$ varies approximately with $d^2$.)

The data points and corresponding envelopes are shown on figure 4 against $N_{Re}$. By plotting the data against $N_{Re}$, the relative magnitude of the $C_{Ds}$ values can be compared to the reference $C_D$ curve for a smooth circular (nonstrumming) cable. Each of the three curves runs approximately parallel to the $C_D$ reference curve, implying that $C_{Ds}$ is independent of water velocity in accordance with equation (4). The data points for these cables fall within a $C_{Ds}$ range of 1.3 to 1.6 and appear to be approximated by a constant factor times $C_D$ as inferred by equation (4) - particularly true for the 0.057 and 0.107 in. diameter cables.

Two additional cables were selected with identical diameters of 0.128 in., but with $d^2/m_c$ ratios of 0.123 and 0.315 $ft^4$/lb $sec^2$. These extreme values were obtained using cables with a mercury filled core and a hollow core, respectively. The cable with the high ratio had a high $C_{Ds}$ envelope, about 2.0 on figure 4, while the low ratio cable had $C_{Ds}$ values falling

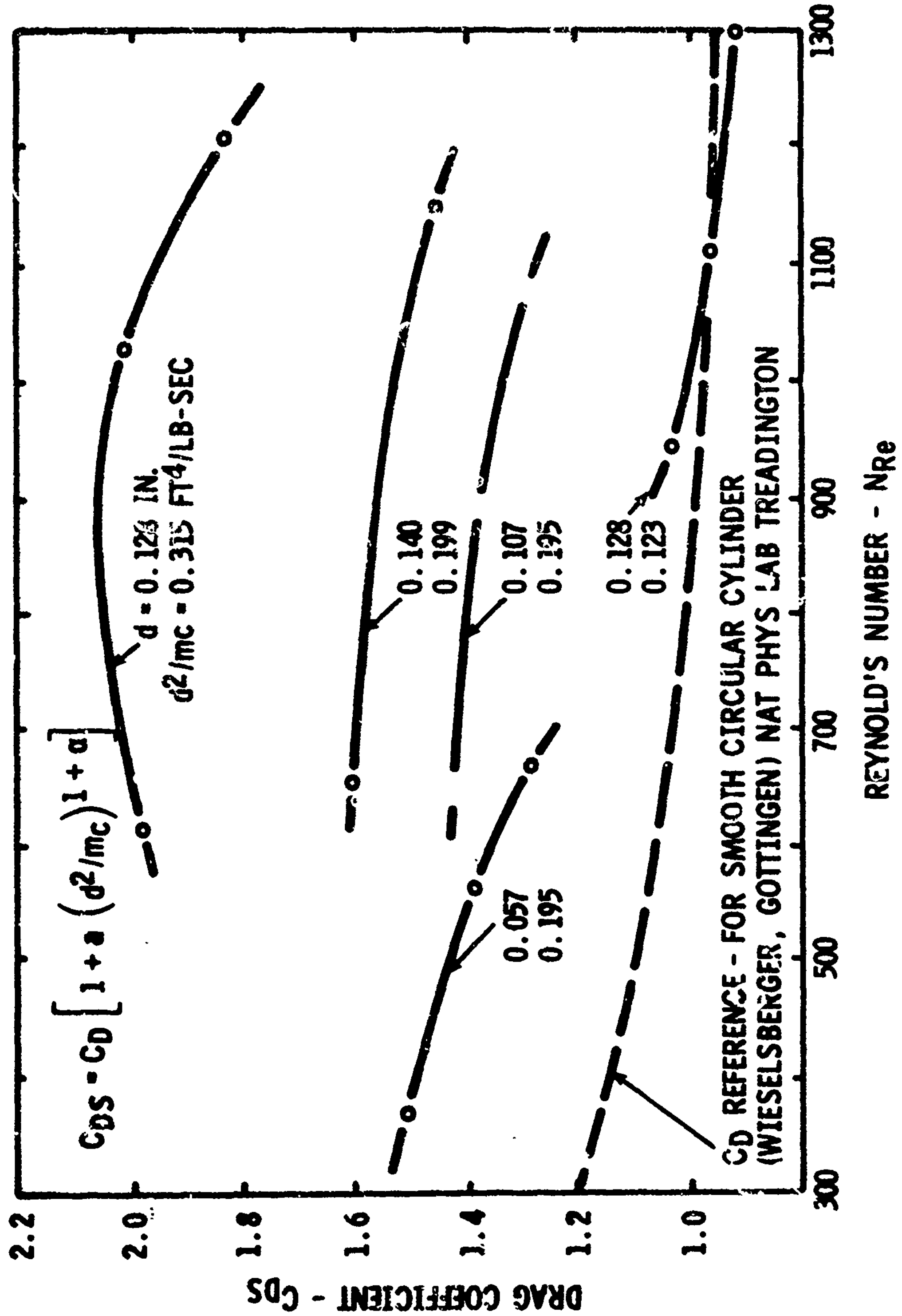


FIGURE 4 - Drag Coefficients of Smooth Circular Strumming Cables

close to the reference $C_D$ curve at about 1.0. Again, the envelopes infer independence of water velocity by paralleling the reference $C_D$ curve. In general, the magnitude of the strumming forces on the fixed end mass showed a direct relationship with the ratio $d^2/m_c$.

To obtain a check on the absolute values of $C_{Ds}$ for the various cables, each cable was tabbed at discrete intervals to minimize the strumming amplitude. (The $C_{Ds}$ values should then fall close to the reference $C_D$ curve. This would check the ability of the drag measuring technique to reproduce the reference $C_D$ curve and add credence to the absolute values of $C_{Ds}$ for the strumming cables.) The test cables were tabbed with 1/2 in. masking tape 1-in. long, applied as localized flow splitters. They were placed at near antinode positions for the range of standing wavelengths expected and a slight correction was made for the localized decrease in $C_D$ caused by the tabs. Most of the resulting $C_{Ds}$ values fell within 5 percent of the $C_D$ curve, with an occasional high or low velocity point falling within 10 percent.

The constants from equation (4), a and $\alpha$ , were evaluated from the data of figure 4. The best fit values were a = 10, $\alpha$ = 1. Using these values in equation (4), predicted values of $C_{Ds}/C_D$ were compared with the measured values of $C_{Ds}/C_D$ in table I. Reasonable correlation was obtained between these ratios for the range of d and $m_c$ tested. If a nominal value for $d^2/m_c$ is 0.195 $ft^4/lb\ sec^2$ for insulated electrical cables, equation (4) reduces to $C_{Ds}/C_D = 1.38$. For a rule of thumb, cable strumming results in approximately a 38 percent increase in the normal drag coefficient.

CABLE PERFORMANCE - SPECIAL DESIGNS

Drag coefficients and strumming force levels have been determined for four cable designs with interesting characteristics. These designs were:

1. twisted pair,
2. antinode splitters,
3. weathervane fairing, and
4. "haired" streamers.

The strumming normal drag coefficients are shown on figure 5 and the periodic strumming forces on figure 6. A physical description is schematically illustrated on figure 5, and values of the respective parameters are plotted with the 0.107-in. diameter smooth circular cable for reference.

Twisted Pair

These data were included because of the simplicity of fabrication. The diameter of each cable was 0.057 in., and the integrated diameter used for the drag coefficient was 0.093 in. Both $C_{Ds}$ and F were lower, compared to the reference cable. Best results were obtained when the pitch was about 15 diameters, based on 0.057-in. diameter.

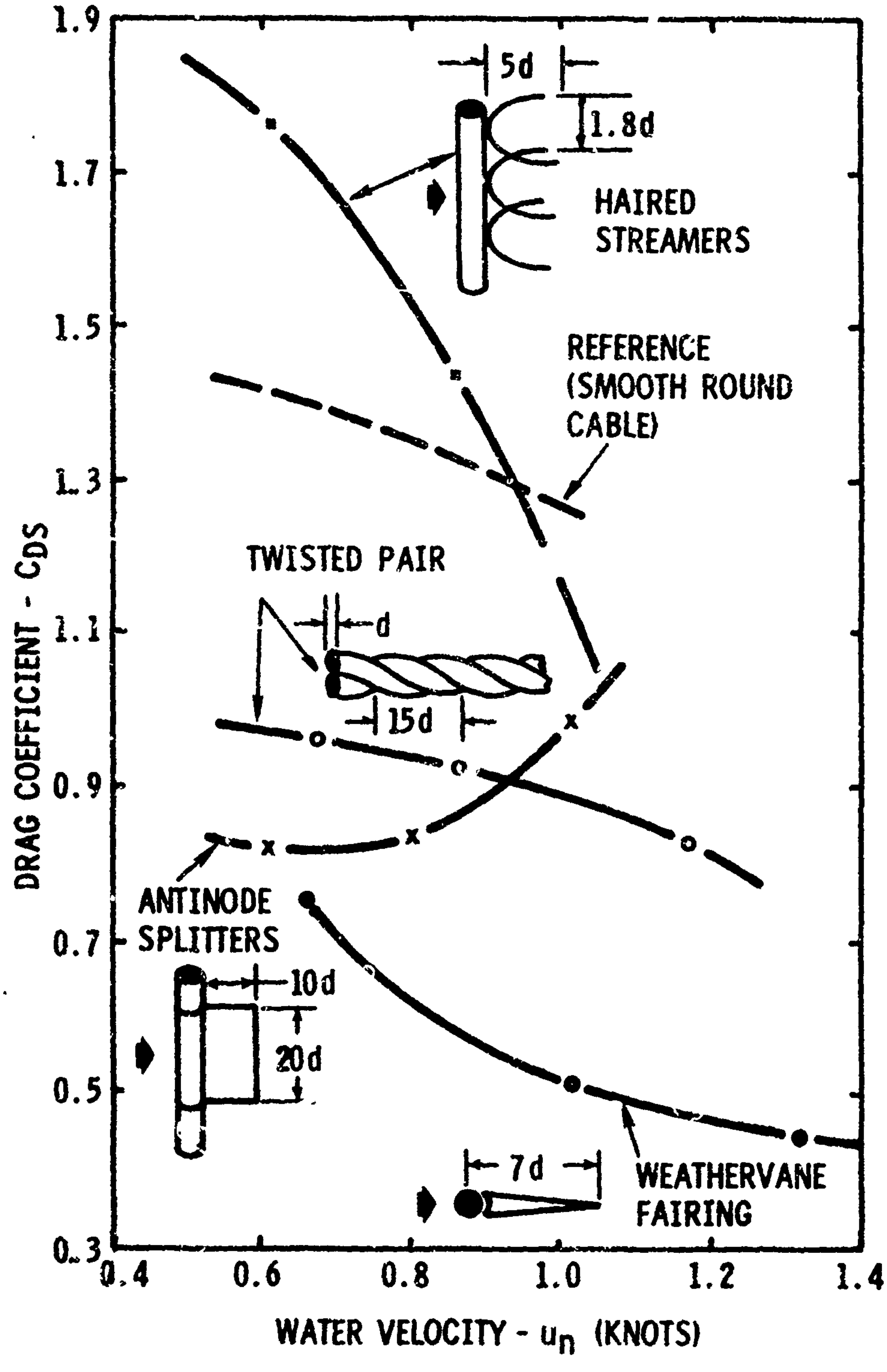


FIGURE 5 - Drag Characteristics of Special Cable Designs

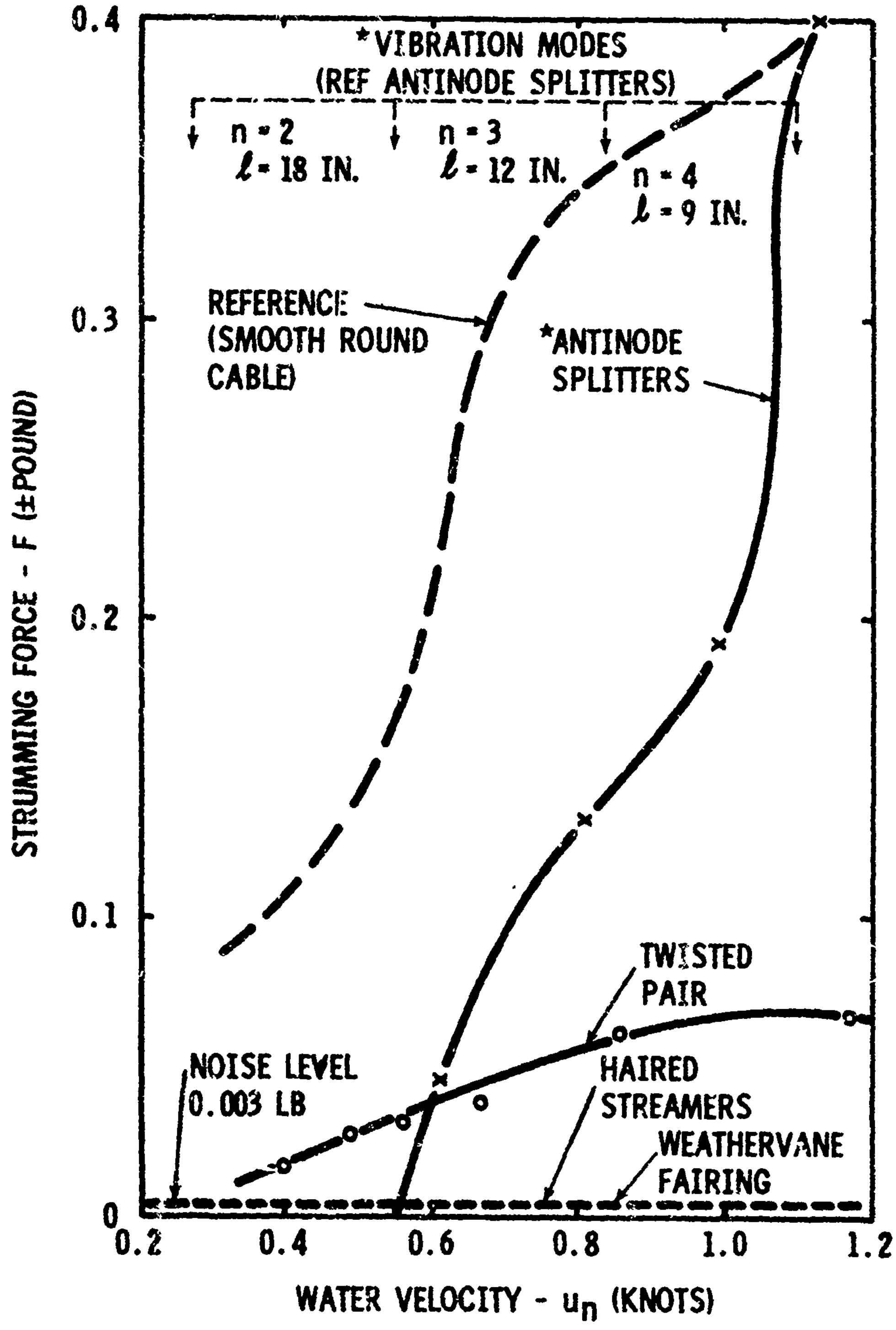


FIGURE 6 - Strumming Force Characteristics of Special Cable Designs

## Antinode Splitters

When localized splitters were attached at the antinodes for a specific partial, the strumming forces at frequencies equal to or less than the partial were less than the noise threshold of ±0.003 lb. Considering the test cable length of 36 in. with a 9 in. tab pitch, this condition existed for partials 1 and 2 with segment lengths of 36 and 18 in., respectively. As the frequency increased to higher partials, the forces became progressively higher, and the level of the nontabbed reference cable was reached when the tabs were at the nodes. This condition was reached at the 4th partial, with a 9 in. segment length. The effect of the higher level strumming at the high velocities was reflected in the $C_{DS}$ plot. The most effective tab geometry was 10 diameters with the stream and 20 diameters along the cable.

## Weathervane Fairing

This was an omnidirectional fairing that was effective in reducing the drag coefficient and kept the strumming force level below the noise threshold of ±0.003 lb.

## Haired Streamers

This was a promising omnidirectional design, because of its simplicity. The hairs were oriented spirally on about a 9-in. pitch. Cotton thread, No. 50 grade, was used for the hairs. The strumming forces were below the ±0.003 lb noise threshold. When the hairs were not spirally attached, best results were obtained with the hairs attached to the downstream edge of the cable. The drag coefficient increased at the lower velocities because the hairs bent outward - their natural position.

## ACKNOWLEDGEMENT

Acknowledgement is made to Mr. G. Goss for his assistance in obtaining and reducing the experimental data.

# APPENDIX A

## DERIVATION OF THE STRUMMING CABLE DRAG COEFFICIENT, $C_{Ds}$

The normal drag coefficient for a strumming cable, considering a unit cable length, is defined as:

$$C_{Ds} = \frac{f_c}{d\rho \frac{u_n^2}{2g}} . \tag{A-1}$$

The transverse standing wave vibrations are illustrated schematically in figure A-1 and are assumed to appear to the flow as a circular non-strumming cylinder with a larger diameter, termed the virtual diameter, $d_V$. The normal drag force per unit length of the cylinder is:

$$f_c = C_D d_V \rho \frac{u_n^2}{2g} . \tag{A-2}$$

Combining equations (A-1) and (A-2) gives:

$$C_{Ds} = C_D \frac{d_V}{d} . \tag{A-3}$$

The virtual diameter is assumed to be the sum of the cable diameter and the increase in diameter resulting from the cable vibrations:

$$d_V = d + \Delta d_p \sigma \tag{A-4}$$

where $\Delta d_p$ is the change in the effective projected diameter (on a plane parallel to the transverse vibrations) and $\sigma$ represents the effectiveness of the flow blockage. Equation (A-3) then reduces to,

$$C_{Ds} = C_D \left(1 + \frac{\Delta d_p}{d} \sigma\right) \tag{A-5}$$

The change in projected diameter $\Delta d_p$ is obtained by dividing the projected area of one wave segment by its length $\ell$. Assuming the cable curvature to be a sine function as illustrated on figure A-1,

$$\Delta d_p = \frac{2}{\ell} \int_0^{\ell} r \sin \frac{y\pi}{\ell} \, dy = \frac{4r}{\pi} \tag{A-6}$$

The $\sigma$ factor is assumed to depend on the ratio of the transverse harmonic cable velocity to the water velocity normal to the cable. By dimensional analysis and application of the Strouhal number,

$$\sigma = a'' \left( \frac{u_t}{u_n} \right)^{\alpha} = a'' \left(2\pi S_t \frac{r}{d}\right)^{\alpha} \tag{A-7}$$

Combining equations (A-5), (A-6), and (A-7),

$$C_{Ds} = C_D \left[1 + a'' \frac{4r}{\pi d} \left(2\pi S_t \frac{r}{d}\right)^{\alpha}\right]$$

or equating the constant to $a'$,

$$C_{Ds} = C_D \left[1 + a' \left( \frac{r}{d} \right)^{1 + \alpha} \right] \tag{A-8}$$

To determine an approximation for the cable amplitude r in terms of physical parameters, each vibrating segment is assumed to be represented as a resonant spring-mass system, or:

$$r = \frac{F}{K_x \sqrt{\left[1 - \left( \frac{\omega}{\omega_n} \right)^2\right]^2 + \left(2 \frac{C}{C_c} \frac{\omega}{\omega_n} \right)^2}} \tag{A-9}$$

For resonance $\omega = \omega_n\sqrt{1 - (C/C_c)^2}$, $K_x$ is approximated as $4T/\ell$ and the magnitude of the lift force F is assumed to be represented by $F = C_L d\ell\rho u_n^2/2g$. Equation (A-9) then reduces to,

$$r = \frac{C_L\rho}{8g \sqrt{4(C/C_c)^2 - 3(C/C_c)^4}} (d\ell^2 u_n^2/T) \tag{A-10}$$

Upon substitution of the string equation (1), and the Strouhal number (2),

$$r = \frac{C_L\rho}{4S_t^2 8g \sqrt{4(C/C_c)^2 - 3(C/C_c)^4}} (d^3/m_c) \tag{A-11}$$

Assuming the coefficient of $d^2/m_c$ to be constant for smooth circular flexible cables equation (A-11) reduces to,

$$C_{Ds} = C_D \left[1 + a \left(d^2/m_c\right)^{1 + \alpha}\right] \tag{A-12}$$

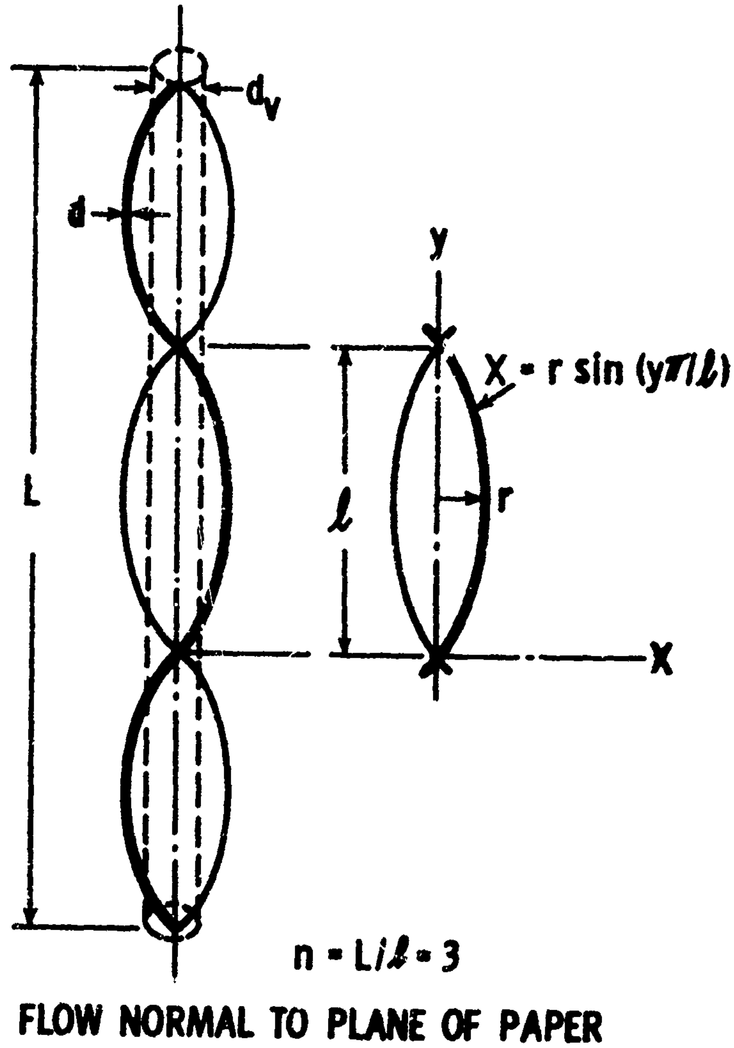


FIGURE A-1 - Analytical Model Showing Transverse Standing Wave Cable Vibrations

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WATER DRAG EFFECTS OF FLOW INDUCED CABLE VIBRATIONS

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PHASE REPORT

5. AUTHOR(S) (First name, middle initial, last name)

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13. ABSTRACT

A study was performed on smooth, circular, flexible cables to determine the water drag characteristics that are dependent upon the cable strumming phenomenon. The test cable diameters ranged from 0.057 to 0.140 in. and the Reynolds numbers were within 300 to 1300. The study was a prerequisite to developing cables with low drag and low strumming characteristics.

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| FLEXIBLE CABLES | | | | | | |
| CABLE FAIRINGS | | | | | | |

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